# Standardization, Diversity, and Learning
# in China's Nuclear Power Program

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Geoffrey Rothwell
Department of Economics
Stanford University, Stanford, CA 94305-6072 USA
rothwell@ stanford.edu

**ABSTRACT**

In the mid-1990s China hoped to build 20 gigawatts (GW) of nuclear generating capacity by 2010 and 30-40 GW by 2020. By the end of the 1990s 2 GW (3 units at 2 plant sites) had been constructed and 6 GW (8 units at 4 plants) were under construction. Four different vendors are supplying the reactors at the four nuclear power plant sites. These vendors are from China, France, Canada, and Russia. In part the multitude of vendors is due to financing constraints. This is leading to a very diverse nuclear power industry, more diverse that the industry in the US, where some believe that diversity lead to increased cost and the inability to compete with other electricity sources. This paper explores the tradeoff between standardization and diversity in the Chinese nuclear power industry, based on David and Rothwell (1996). If the current Chinese nuclear power program can be interpreted as the first stage of a multi-stage project, where later stages will standardize on a single design, we could interpret the current Chinese strategy as one of optimal experimentation, but this optimality depends on developing a program to maximize learning from the diversity of these nuclear power technologies.

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**1. Chinese Nuclear Power Program during the 1990s**

In the 1980s China began constructing two Pressurized Water Reactor (PWR) nuclear power plants (NPPs): Qinshan 1 on the central China coast and Daya Bay near Hong Kong. See Table 1. Qinshan 1 was built by the China National Nuclear Corporation (CNNC), converting a Chinese submarine reactor design to a nominal 300 megawatt-electric NPP with a net capacity of 279 MW (net megawatts). Given the high local content, it had a low initial capital cost, but imported capital additions increased the cost significantly. On the other hand, the two 944 MW units at Daya Bay were built with expensive foreign equipment and engineering from France and the UK through Framatome (of France) and a joint venture of General Electric Company (of the UK) and Alcatel-Alsthom (of France) with French and British financing. Both plants came into commercial operation in 1994. Both had problems in early operation. These problems were solved by 1995. Both were operating at high capacity factors through 1997 (see Rothwell 1998), but there have been problems at Qinshan 1 since 1998.

The Chinese and the international nuclear equipment and services suppliers were optimistic about the future of nuclear power in China in 1996 when China published its Ninth Five-Year Plan (1996-2000), see Suttmeier and Evans (1996). It called for constructing 8 more units at 4 sites before the year 2000. These are (1) Qinshan 2, a follow-on to Qinshan 1 with two 610 MW PWR units; (2) Ling'ao, a follow-on to (and near) Daya Bay with two 935 MW PWR units with French and British technology and financing; (3) Qinshan 3, a Canadian Pressurized Heavy Water Reactor (PHWR), similar to units in (the Republic of) Korea, with Canadian financing; and (4) Lianyungang (between Qinshan and Beijing), a Russian 950 MW

WWER (a pressurized water cooled and moderated reactor) with Russian financing. See Sinton (1998).

Further, the CNNC was optimistic that China would build 20,000 MW of nuclear capacity by 2010 and 30,000-40,000 MW by 2020, for example, by finishing 8 units with 6,000-8,000 MW every five years from 2000 to 2020. This optimism carried over to the international (Asian and European) community. Although US nuclear equipment suppliers were closed out of the Chinese market because of non-proliferation restrictions on the export of US nuclear technology to China, Westinghouse signed an agreement in 1995 to supply turbine-generators for the Qinshan 2 plant and US engineering services supplier, Bechtel, was awarded the "balance-of-plant" design contract for Qinshan 2 in 1996. In October 1997 the US and China concluded an agreement that allowed US nuclear steam system supply (NSSS) manufacturers to export nuclear equipment to China on a case-by-case basis. The US nuclear power industry was elated to be able to enter the "$60 billion dollar" market (see Winston and McManamy, 1997) [1]. However, no major projects were awarded to US NSSS suppliers before 2000.

In early 2000 the Beijing government requested the leading Chinese nuclear industry participants to focus on the development of a standardized PWR by 2002. Unless this NPP is defined soon, it is unlikely that the Tenth Five-Year Plan (2001-2005) will include many new plants because (1) none of the plants in the Ninth Plan have been completed, (2) demand growth for electricity has slowed as Chinese heavy industry has restructured, (3) international finance for nuclear power plants has been difficult to obtain, (4) Chinese national policy has shifted attention away from building generating capacity to improving the transmission and distribution system, and (5) the Chinese nuclear licensing and regulatory agency, the National Nuclear Safety

Administration (NNSA) is overwhelmed with the diversity of the nuclear technologies under construction. See Hibbs (1999a, 2000a) and Suttmeier and Evans (1998). International optimism regarding a nuclear power boom in China has waned.

Has the strategy of building a nuclear power industry in China been successful? Should China have focused earlier on a standardized design, as the French did in 1974? This paper examines the optimality of China's approach based on David and Rothwell (1996a). The next section compares Chinese diversity with other national nuclear programs. Section 3 parameterizes the Chinese strategy with a model where a central planner attempts to minimize the present value of construction and operation costs by choosing the optimal level of diversity. The model examines the trade-off between "learning-by-doing" in the construction of standardized nuclear power units and "learning-by-using" many nuclear power technologies to increase the probability of discovering the least cost NSSS design in a particular national context. The model shows that the optimality of the diversity approach depends crucially on the ability of Chinese nuclear power industry to incorporate learning into a standardized design. The issue of how to maximize learning is discussed in Section 4.

## 2. Standardization in Commercial Nuclear Power

Diversity in nuclear power plant design can be examined along at least four dimensions: (1) the nuclear fuel, (2) the moderator of the nuclear reaction, (3) the nuclear reactor coolant, and (4) the method of transforming heat from the reactor into electricity. In operating nuclear power plants the nuclear fuel is (1.1) natural uranium or (1.2) enriched uranium.[2]. The nuclear reaction is moderated with (2.1) graphite (carbon), (2.2) liquid metal (e.g., sodium), (2.3) light (ordinary) water, or (2.4) heavy water (deuterium, an isotope of hydrogen, enriched water). The nuclear reactor can be cooled with (3.1) gas (e.g., helium), (3.2) light water, (3.3) heavy water, or (3.4) liquid metal. The heat from the coolant can be converted to electricity (4.1) with a gas turbine, (4.2) with a liquid coolant that boils in the reactor pressure vessel and passes directly to a turbine, or (4.3) with a non-boiling liquid, where the coolant does not boil in the reactor vessel (e.g., by keeping it under pressure) and its heat is transferred to a separate circuit of water using “steam generators” or “heat exchangers.”

Although there have been many experimental designs combining these options, current operating designs are (1) Pressurized light Water cooled and moderated Reactors using enriched uranium, PWRs and WWERs (a Soviet-designed pressurized Water cooled, Water moderated Electricity Reactor); (2) Boiling light Water cooled and moderated Reactors using enriched uranium, BWRs and Advanced BWRs (ABWRs); (3) Graphite moderated Reactors (GRs) of many types, including the early British and French Gas-Cooled Reactors, GCRs, later British Advanced Gas Reactors, AGRs, and the Soviet-designed water-cooled RBMK, for example at Chernobyl; (4) Heavy Water moderated Reactors (HWRs), including the Canadian Pressurized Heavy Water Reactor, PHWR or CANDU, using natural uranium, and (5) the Fast Breeder Reactors (FBRs) using liquid sodium. As shown in Figure 1, current world operating capacity includes PWRs (196 GW, 207 units), BWRs (79 GW, 92 units), WWERs (31 GW, 48 units), GRs (27 GW, 54 units), HWRs (16 GW, 32 units), and FBRs (1 GW, 4 units). See IAEA (2000).

World nuclear power diversity can be measured with a Herfindahl-Hirschman Index (HHI) used in studies of industrial concentration, as in David and Rothwell (1996b). It is defined as the sum of the squared market shares: $\Sigma\, s_j^2$, where $s_j$ is the market share (of capacity) of a reactor type *j*. Figure 2 shows changes in the world HHI from 1960 through 2005 (considering nuclear units under active construction). Until the early 1970s the graphite reactor had the largest nuclear power market share. However during the 1970s, the PWRs surpassed GRs and light water reactors (PWRs, BWRs, and WWERs) and now dominate world nuclear power.

As noted above, the French chose the PWR as their standardized design in 1974 and have closed all of their earlier graphite reactors (with a current HHI of 0.99, including a 233 MW FBR). This can be represented in a graph of the French HHI from 1960 to 2005. Figure 3 shows the HHIs of nuclear programs in Canada, France, Russia, and the US. The Canadian nuclear industry has always relied on the HWRs (HHI = 1.00). Russian capacity (HHI = 0.48) is almost evenly split between the RBMK (10 GW) and the WWVER (9 GW) with one FBR (560 MW). The US HHI is slightly higher at 0.56 with 67 GW of PWRs and 32 GW of BWRs. [3]

These programs can be compared with those in East Asia. See Figure 4. Japan is more diverse (HHI = 0.51) than the US with ABWRs and BWRs (26 GW), PWRs (18 GW), one operating HWR (148 MW), and a FBR (246 MW). South Korea has a more standardized industry (HHI = 0.71) with PWRs (10.4 GW with 1.9 GW under construction) and PHWRs (2.6 GW). Taiwan has 6 ABWRs and BWRs (3.1 GW with 2.6 GW under construction) and 2 PWRs (1.8 GW) with a HHI of 0.54, increasing to 0.64 by 2004. Although China now only operates PWRs, when all of the units now under construction are completed, the HHI will fall to 0.46, i.e., it will have the least standardized nuclear power industry in East Asia under this measure of diversity. The next section models the benefits and opportunity cost of this diversity.

## 3. Standardization and Diversity in the Chinese Commercial Nuclear Power Program

To evaluate China’s nuclear power strategy, I apply the model in David and Rothwell (1996a) to China’s Ninth Five-Year Plan. The primary assumption is that the central nuclear power planner's goal is to minimize the present value of building and operating a nuclear power industry. The problem can be simplified by considering a two-generation program: In the first stage of Generation I *N* plants are built. In the second stage these plants are operated at costs that depend on the degree of standardization. In Generation II, one technology type is selected and *X* sets of *N* plants are constructed. What level of diversity is optimal in Stage 1?

### 3.1. Generation I

#### 3.1.1. Stage 1: Construction

In Stage 1 a total of $N$ nuclear power units are built with $n$ units of $M$ types: $N = n \cdot M$. If the total number of units ( $N$ ) is given exogenously (e.g., by projected electricity demand), the planner’s problem can be characterized as either choosing the optimal number of technology types ( $M$ ) or, equivalently, choosing the optimal level of diversity, where diversity ( $d$ ) can be measured as ( $M / N$ ). Alternatively, standardization can be measured as ($1/ M$ ) and, under the assumption of an equal number of units of all types, it is equal to the HHI. The planner can choose between two extremes: (1) no diversity, or complete standardization (following the French example, see David and Rothwell, 1996b), where $d = 1/N$, and (2) complete diversity, where $d = 1$.

To determine the optimal level of diversity, assume that (1) there is an equal number of units of all types $n_j = n$, where $j = 1, \ldots, M$, and (2) first-of-a-kind construction costs (in dollars per net megawatt-electric, MW) are the same for each type ($k_j = k$ for all $j$ ), where *k includes* financing costs during the construction period. For example, $k$ = \$2,400 per net kW or \$2.4 million (M) per MW. Further, assume all units are built *simultaneously* during the construction period, equal to $\tau$ years, for example, $\tau = 5$ years beginning in 1995. Here, learning in construction activity is equivalent to economies of scale in the number of units, so that

$$k_n = k\ n^{-\gamma}, \quad 0 < \gamma \leq 1 , \qquad (1)$$

where $k_n$ is the construction cost per MW (at the end of Stage 1, *including* finance charges during construction) for a set of $n$ units of a single type and $\gamma$ is a measure of learning. For example, if $\gamma = 0.10$, $k_1$ = \$2,400/kW, $k_2$ = \$2,239/kW, $k_4$ = \$2,089/kW, $k_8$ = \$1,949/kW, etc., see Table 2b. (This approximates experience in China; see Table 1.) The total cost of each *set* of units is

$$n\ W\ k_n = n\ W\ k\ n^{-\gamma} = W\ k\ n^{1-\gamma}, \qquad (2a)$$

where W is the size of each unit in MW. The total cost ( $K$ ) of building all $N$ plants, assuming all units are the same size, is

$$K = M\ (\ W\ k\ n^{1-\gamma}\ ) = M\ W\ k\ (\ N/M\ )^{1-\gamma} = N\ W\ k\ (\ M/N\ )^{\gamma} = N\ W\ k\ d^{\gamma}\ . \qquad (2b)$$

For example, for a program of eight 900 (net) MW units with first-of-a-kind costs of \$2,400/kW and $\gamma = 0.10$ yields a total cost of \$17 billion (B) with total diversity ($d$ = 1.0) and \$14B with total standardization ($d$ = 0.125): total cost increases with diversity. See Table 2b. With a 30-year life and a *real* rate of return of 7%,[4] the capital recovery factor would be 8%.[5] With a 80% capacity factor (see Rothwell, 1998) the capital cost per megawatt-hour (MWh) would be \$28/MWh with total diversity and \$23/MWh with total standardization.[6]

### 3.1.2. Stage 2: Operations and Incremental Learning

In Stage 2 of Generation I the focus is on minimizing the cost of generating electricity at units built in Stage 1. Generating costs per MWh are composed of two parts: a capital (construction) cost and an annual operations cost.[7] The capital cost per MW is $k\,d^{\gamma}$. The annual cost reflects an initial cost ( $c$ ) minus a cost saving ( $cs$ ), anticipated and optimized in Stage 1, and thus realized from the beginning of Stage 2. Assume that initial operations cost, $c_j$, is equal to an average $c$ for all types. However, for each level of diversity the cost savings component ( $cs_j$ ) varies with differences in learning-by-using: $cs_j$ is a function of the number of units constructed of each type. Operation yields learning opportunities that generate a distribution of attainable cost savings. A larger number of units of a particular type leads to more experience and to an increase in the probability of discovering the *least cost* method of producing electricity *in a particular context* (such as China): $\partial F(cs_j)/\partial n > 0$, where $F(cs_j)$ is the cumulative distribution function of attaining the *maximum* cost savings for each technology.

If cost savings, $cs_j$, are distributed with mean $\mu_j$ and variance $\sigma_j^2$, the expected *maximum* cost savings for units of type $j$ is $\mathrm{E}(cs_j^{\max} \mid n)$. What is the relationship between $cs_j^{\max}$ and $n$? Making use of a general result regarding extreme value distributions, the expected extreme value is a positive function of the mean and the standard deviation, when such samples are drawn from a unimodal distribution (see Gumbel 1958). Also, the expected extreme value is a positive concave function of the sample size ( $n$ ): The effect of increasing sample size interacts positively with the standard deviation of the underlying distribution.[8] Assuming normality, the expected maximum improvement from experienced-based learning for each type can be modeled as [9]

$$\mathrm{E}\,(\, cs^{\max} \mid n\,) = \mu + \sigma\,(\log n\,)\,,\ \text{for}\ \ n \geq 1\ . \qquad (3)$$

Assume that $\mu = 0$ for all types (the mean cost savings is absorbed into $c$ at the beginning of Stage 2). Then the annual cost and realized cost savings in Stage 2 per MWh are

$$\begin{aligned} C_2 &= c - \mu - \sigma \log n &&= c - \sigma \log (N/M) \\ &= c - \sigma\,(-\log (M/N)\,) &&= c + \sigma \log d\ . \qquad (4) \end{aligned}$$

For $N$ units of capacity $W$ the total operations cost per year is $N\,W\,C\,h$, where $h$ is the hours per year, usually 8,760. For example, assume that $N$ = 8, $W$ = 900, $c$ = \$40/MWh, and $\sigma$ = \$4/MWh. With total diversity, $C_2$ = \$40/MWh and total Generation I operating costs are \$2.5B per year. With total standardization, $C_2$ = \$32/MWh and total operating costs are \$2.0B per year. See Table 2b. Under these assumptions, total cost per MWh would be \$55 with total standardization and \$68 with total diversity. This is similar to the price of power from Daya Bay at \$68/MWh, see Hibbs (1999b).

These costs are discounted to the beginning of Stage 2 by $\delta_2(\, r\,,\, \tau_2\,)$, where $\delta_2$ is a uniform series, present value factor that depends on the discount rate, $r$, and the life of the nuclear unit, $\tau_2$.[10] The present value of costs at the beginning of Stage 2 ( $PV_2$ ) for the $N$ plants is

$$PV_2 = N\,W\,\{\ k\,d^{\gamma} + \delta_2\,h\,[\, c + \sigma\ \log d\ ]\ \}. \qquad (5)$$

With a 30-year life and a 7% real rate of return, $\delta_2(\, r\,,\, \tau_2\,)$ = 12.10. $PV_2$ is \$48B with total diversity, but $PV_2$ is only \$38B with total standardization, see Table 2b. Diversity drives up expected costs during Generation I: $\partial PV_2 / \partial d > 0$. Under what circumstances is diversity beneficial for a second generation?

### 3.2. Generation II -- Construction and Operation

There will be some point when it is optimal to choose a standardized plant design: that point is the start of Generation II. Generation II could start at any time after Stage 1 of Generation I. For example, Generation II could start 5 years into Stage 2 (e.g., after a single 5-year plan). Define the start of Generation II to be $\tau_4$ years since the start of Stage 1 (for example, 10 years after the start of Stage 1 in 1995). In Generation II, assume the following.

(1) ( $X \cdot N$ ) units are built at a rate of $N$ units per stage with $X$ stages in Generation II every $\tau$ years.

(2) Construction costs for all units in each stage of Generation II are equal to the previous generation's "n-th-of-a-kind" costs, where "n" is the number of units completed through the end of the previous stage and the rate of learning is the same as in Generation I.

(3) Opportunities to observe different nuclear power plant types in Generation I make it possible to select the best design.

(4) Operation of the type of plant selected for standardization yields the same distribution of potential cost reductions with the expected maximum improvement exceeding that available in the second stage of Generation I only if there was more than one technology type built in the first stage of Generation I.

Corresponding to assumptions (1) and (2), the construction costs per MW for $N$ units of a single type built in each stage of Generation II would be

$$k_x ( N \mid m ) = ( k\, d^{\gamma} ) \; ( x N )^{-\gamma} \; , \tag{6}$$

where $x = 1, \ldots, X$ and $( x N )^{-\gamma}$ represents learning in constructing units of a single type. For example, if $\gamma = 0.1$, $k_2$ = \$2,089/kW in Stage 1, and 32 units ( $X = 4$ ) are built in Generation II, the *average* cost per unit would be \$1,570/kW. With an 80% capacity factor the average capital cost per MWh would be \$21/MWh with total diversity and \$17/MWh with total standardization.

Corresponding to assumptions (3) and (4), the selection of the type of plant with the largest expected (single plant) cost reduction can be represented as a draw from the extreme value distribution. The expected mean cost savings is [11]

$$\mathrm{E}(cs_3^{\max} \mid M ) = \mu + \sigma M^{\alpha} \; , \quad 0 < \alpha < 1 \; , \tag{7}$$

where $\alpha$ is a measure of learning from diversity in operating many types of Generation I plants. Here, diversity during Stages 1 and 2 permits more learning, reducing operating costs during Generation II: in developing a standardized Chinese nuclear generating station, more diversity would be beneficial in Stage 1. Unlike in Generation I where $\mu = 0$, in Generation II cost savings cumulate from Generation I, so $\mu = -\sigma \log d$ and annual cost per MWh is

$$C_3 = c + \sigma \log d - \sigma M^{\alpha} . \tag{8}$$

For example, assume $c$ = \$40/MWh, $\sigma$ = \$4/MWh, and $\alpha = 0.5$. With total standardization in Generation I, $C_3$ = \$28/MWh. With total diversity in Generation I, $C_3$ = \$29/MWh. Under these assumptions, total cost would be \$45/MWh with total standardization in Generation I and \$50/MWh with total diversity. These are similar to the cost of electricity from new coal plants, see May, Heller, and Zhang (1999) and are under the Chinese goal of \$55-\$60/MWh (Hibbs 1999b).

These costs are discounted to the beginning of Generation II by the factor $\delta_3( r ,\tau_3 )$. For example, as in Generation I, assuming a 30-year life and a 7% *real* rate of return, $\delta_3( r , \tau_3 ) = 12.10$. The expected present value *at the beginning* of Generation II, $PV_3$ , for the $X \cdot N$ plants is

$$PV_3 = \Sigma e^{-r x \tau} N W \{ ( k d^{\gamma} ) ( x N )^{-\gamma} + \delta_3 h [ c + \sigma \log d - \sigma M^{\alpha} ] \} \qquad (9)$$

for $x = 1, \ldots X$. For example, with parameter values equal to those in Table 2a with total diversity in Generation I $PV_3$ = \$98B and with total standardization $PV_3$ = \$89B. With these parameter values, early standardization is the least cost option for this multi-stage program. This depends on the scale parameter $\gamma$ and the learning parameter $\alpha$. The next section explores optimal diversity as a function of $\gamma$ and $\alpha$.

### 3.4. Optimal Diversity

Again, what is the cost-minimizing value of $M$, the number of different plant types to build in Stage I? To answer this question, define continuous-compounding discount factors, $\delta_1 = e^{-r\tau}$, which translates second stage Generation I costs to the start of the program, and $\delta_4 = e^{-r\tau 4}$, which translates start of Generation II costs to start of program present value equivalents. Expressing all costs at the beginning of the program (see Equations 5 and 9),

$$PV^* (N|M) = \delta_1 N W \{ k d^{\gamma} + \delta_2 h [ c + \sigma \log d ] \}$$

$$+ \delta_4 \Sigma e^{-r x \tau} N W \{ ( k d^{\gamma} ) ( x N )^{-\gamma} + \delta_3 h [ c + \sigma \log d - \sigma M^{\alpha} ] \}. \qquad (10a)$$

Considering costs per MW and substituting for $d = (M/N)$, Equation (10a) becomes

$$c^*(N|M) = \delta_1 \{ k(M/N)^{\gamma} + \delta_2 h [c + \sigma \log(M/N)] \}$$

$$+ \delta_4 \Sigma e^{-r x \tau} \{ k(M/N)^{\gamma} (xN)^{-\gamma} + \delta_3 h [c + \sigma \log(M/N) - \sigma M^{\alpha}]\}, \qquad (10b)$$

where $c^* = PV^*/NW$, i.e., the present value of cost per MW.

The first order condition for a minimum (or maximum) is given by $\partial c^* / \partial M = 0$. The first derivative is

$$\partial c^* / \partial M = q_1 \gamma M^{\gamma - 1} + q_2 M^{-1} - q_3 \alpha M^{\alpha - 1} = 0, \quad \text{where} \qquad (11a)$$

$$q_1 \equiv k N^{-\gamma} [\delta_1 + \delta_4 \Sigma e^{-r x \tau} x^{-\gamma} N^{-\gamma}],$$

$$q_2 \equiv h \sigma [\delta_1 \delta_2 + \delta_3 \delta_4 \Sigma e^{-r x \tau}], \quad \text{and} \quad q_3 \equiv h \sigma [\delta_1 \delta_3 \Sigma e^{-r x \tau}] .$$

Note that $q_1$, $q_2$, and $q_3$ are positive. Next, the second order condition for a minimum is $\partial^2 c^* / \partial M^2 \equiv \Delta > 0$. The second derivative is

$$\Delta = q_1 \gamma (\gamma - 1) M^{\gamma - 2} - q_2 M^{-2} - q_3 \alpha (\alpha - 1) M^{\alpha - 2}$$

$$= -q_1 \gamma (1 - \gamma) M^{\gamma - 2} - q_2 M^{-2} + q_3 \alpha (1 - \alpha) M^{\alpha - 2}. \qquad (12)$$

The first two terms on the right hand side are negative, but the third term is positive. Therefore, whether $\Delta$ is greater than, equal to, or less than zero depends on where the second order partial is evaluated. To evaluate the expression for $\Delta$ where $\partial c^* / \partial M = 0$, multiply Equation (11a) by $(1 - \alpha) M^{-1}$ and rearrange:

$$q_3 \alpha (1 - \alpha) M^{\alpha - 2} = q_1 (1 - \alpha) \gamma M^{\gamma - 2} + q_2 (1 - \alpha) M^{-2} \qquad (11b)$$

Substituting this into Equation (12) yields

$$\Delta = q_1 (\gamma - \alpha) \gamma M^{\gamma - 2} - q_2 M^{-2} \alpha . \qquad (13)$$

The sign of $\Delta$ in Equation (13) depends on the sign of $(\gamma - \alpha)$. There are two main cases and two sub-cases:

**Case 1**: $(\gamma - \alpha) \leq 0$ implies that both terms in Equation (13) are negative, so no interior cost-minimizing value for $M$ exists. Under these conditions there are two sub-cases.

**Case 1a** in which the lowest costs are achieved where only one type of plant is built from the outset: $M = 1$ and $d = 1 / N$.

**Case 1b** in which maximum diversity is cost minimizing: $M = N$ and $d = 1$.

**Case 2**: $(\gamma - \alpha) > 0$ is necessary, but not sufficient, for the existence of an interior optimum for the value of $M$.

First, considering Case 1, to determine whether $M = 1$ or $M = N$ yields the lowest cost, evaluate $c^*(N \mid M)$ at the two extremes and examine the difference:

$$
\begin{aligned}
c^*(N \mid M = 1) - c^*(N \mid M = N) = & - \delta_1 k (1 - N^{-\gamma}) - \delta_1 \delta_2 h \sigma \log N \\
& - \delta_4 \Sigma e^{-r x \tau} k (x N)^{-\gamma} (1 - N^{-\gamma}) \\
& + \delta_3 \delta_4 \Sigma e^{-r x \tau} h \sigma (N^{\alpha} - 1 - \log N), \quad x = 1, \ldots, X \qquad \text{(14a)}
\end{aligned}
$$

Here, if $c^*(N \mid M = 1) - c^*(N \mid M = N) > 0$, then the cost of total diversity would be less than the cost of total standardization. Is there an $\alpha$ such that the present value of total program costs could be minimized with total diversity? The first three terms on the right hand side are negative, so for $c^*(N \mid M = 1) > c^*(N \mid M = N)$, $(N^{\alpha} - 1 - \log N)$ must be positive. For $N = 8$, $\alpha$ must be greater than 0.54. Second, solving for $\alpha$ in Equation (14a):

$$\alpha \quad = \quad (1/\log N)\cdot\log\{1+\log N + (1/\delta_3\,\delta_4\,\Sigma\, e^{-r\,x\,\tau} h\,\sigma)\cdot[\delta_1\, k\,(1-N^{-\gamma})$$

$$+\ \delta_1\,\delta_2\, h\,\sigma\,\log N\ +\ \delta_4\,\Sigma\, e^{-r\,x\,\tau} k\,(x\,N)^{-\gamma}(1-N^{-\gamma})\,]\,\}\,. \qquad (14b)$$

With the parameter values in Table 2a, at $\alpha = 0.82$ the present value of program costs are equal for total standardization and total diversity. With $\alpha > 0.82$ total diversity yields a lower present value. See Figure 6. Therefore, with $(\gamma - \alpha) \leq 0$, the coefficient of learning during operations must be *very high* for diversity to be the optimal strategy.

Next, consider Case 2 in which $(\gamma - \alpha) > 0$ satisfies the necessary condition for the $PV^*$ to be strictly minimized by selecting some initial level of design diversity, i.e., $M > 1$. However, for a strict minimum, $(\gamma - \alpha) > 0$ is not sufficient. The second order condition ( $\Delta > 0$ ) must be satisfied where $\partial c^* / \partial M = 0$. From Equation (13), the second order condition is satisfied when

$$q_1\,(\gamma - \alpha)\,\gamma M^{\gamma} - q_2\,\alpha > 0 \qquad (15)$$

Solving the first order condition for $M^{\gamma}$ from Equation (11a) and substituting into Equation (15), the condition for a strict minimum of c* is

$$(\gamma - \alpha)\,(q_3 / q_2)\,\alpha\, M^{\alpha} - \gamma > 0 \quad \text{with} \quad \gamma > \alpha\,. \qquad (16)$$

Are there values for $\alpha$ that can satisfy this condition? Given $0 < \gamma \leq 1$ and $0 < \alpha < 1$, the least restrictive value of $\gamma$ for evaluating $\alpha$ would be $\gamma = 1$. Substituting $\gamma = 1$ into (16a) yields

$$A \quad = \quad (1 - \alpha)\,(q_3 / q_2)\,\alpha\, M^{\alpha} - 1 > 0 \quad \text{with} \quad 1 > \alpha \qquad (17)$$

Figure 7 plots values of $A$ for $\alpha = 0.1$ through 0.9 with $\gamma = 1$. There are no values where the second order condition for Case 2 satisfied. Therefore, with reasonable parameter values, there is no interior optimum value for $M$. The optimum is either **Case 1a**: complete standardization in

Generations I and II, or **Case 1b**: complete diversity in Generation I with standardization in Generation II. The optimality of complete diversity (**Case 1b**) depends on *high* values for $\alpha$, i.e., an expectation that diversity in Generation I will yield a *large* reduction in cost in Generation II.

## 4. Policy Conclusions and Further Research

Two sets of conclusions flow from this analysis. The first concerns standardization, diversity, and learning in China's commercial nuclear power program. The second concerns the applicability of the model in David and Rothwell (1996a) to industrial policy.

Like most economic analyses of industrial policy, I assume that the objective of the nuclear power planners in China is to *maximize Chinese social welfare*. This involves minimizing the price of electricity, maximizing the profitability of the enterprises involved with the industry, and encouraging industrial development in China. All of these goals coincide with policies that lead to the efficient allocation of resources.

The interpretation of these objectives by state planners in China has lead to the following policies: (1) minimize the investment of Chinese capital in building and operating nuclear power plants, (2) minimize state subsidies to Chinese enterprises in the nuclear power industry by breaking up state enterprises into commercially viable entities and relying on domestic and international competition to discipline these firms, and (3) increase local content and technology transfer with each new contract with an international supplier.

This has resulted in a nuclear power industry with a Chinese prototype (Qinshan 1 and 2), a Chinese-French hybrid (Daya Bay and Ling'ao), and competing international designs

(Qinshan 3 and Lianyungang). Presently, the stated goal (Hibbs 2000b) is to develop a Chinese standard nuclear plant (CSNP) to be defined in the final or revised draft of the Tenth Five-Year Plan.[12] For 20,000 MW of capacity by 2010, *at least* 4 new units should be started in the Tenth Five-Year Plan to avoid equipment and personnel bottlenecks in building 8 more units in the Eleventh Five-Year Plan (2006-2010).

While the construction cost per kilowatt has been declining for the French-Chinese hybrid, Chinese electricity consumers will pay dearly (in present value terms) for this program unless the CSNP can be developed at minimum cost with maximum learning. The model discussed here demonstrates that initial standardization would be cheaper than initial diversity unless there is tremendous learning from the Generation I plants. The model has focused on learning from diversity in operations. A model with learning from diversity in engineering design and construction would likely lead to the same conclusions.

Unfortunately, there is a conflict between (1) the goal of developing a CSNP that relies on learning through *cooperation* and (2) a strategy that minimizes cost through *competition* (for example, minimizing Chinese capital by encouraging competition among international suppliers to provide financing or lower project cost). This conflict is present in most research and development programs. Given the diversity and competition in the Chinese nuclear power program, how can learning now be maximized (i.e., how can the value of $\alpha$ be increased)?

First, the Chinese should recognize the experimental nature of their situation and treat the Generation I as a scientific program, not simply a commercial one, i.e., they should use scientific and engineering standards of evaluation, as well as profitability. The standard design should include a standardized construction program with modularization and virtual construction. These aspects of the program can be learned from construction at all NPP sites in China.

Second, the Chinese should develop standards for acquiring and analyzing information on *all* aspects of construction, operation, and regulation, including problems encountered, possible solutions considered, the process of determining the solution to each problem, and the success of each chosen solution. For example, IAEA (1999) outlines a method of studying management practices at nuclear power plants (see the "Wolsong Case Study" in IAEA, 1999). Similar studies should be conducted on construction management (including equipment acquisition, scheduling, and human resources), operation (including equipment quality and reliability), and regulation (including probability risk assessment and risk-informed regulation). This information can be used to integrate standardized building, training, operating, and licensing procedures.

Third, the Chinese should develop a long-term plan for a standardized design that specifies equipment and services that can be provided by *more than one* supplier domestically or internationally and subject to competitive bidding. A standard design that relies only on monopoly suppliers will not be able to compete with other forms of electricity generation either because construction costs will not decline with scale or operating costs will not improve (for example, through increases in productivity).

Finally, the second purpose of this paper was to test the applicability of the model in David and Rothwell (1996a). While the model successfully captured many aspects of the problem of designing a present-value-minimizing industrial policy, its focus on tractability reduced its ability to represent China's nuclear power program. Therefore, future research should address the following issues. First, sensitivity analysis should be conducted and simplifications made to improve tractability and realism. Second, the model of “learning-by-using” in operations relies on extreme value statistics. Therefore, the model should be embedded in a probabilistic framework, i.e., probability distributions should be specified for key variables and parameters and Monte Carlo simulations should be performed to determine the robustness of the conclusion regarding optimal diversity in Generation I. Third, the Chinese program has been hampered by capital constraints. The implicit assumption here has been perfect capital markets. The model should incorporate financing constraints and be solved using constrained optimization techniques. Fourth, the model should be embedded in an industrial organization framework where the incentives of international technology suppliers are incorporated and the observed outcome can be interpreted as an equilibrium between Chinese planners and international interests. These features will provide a more realistic model in which to evaluate standardization, diversity, and learning in the evolution of technologies such as commercial nuclear power in China.

**ENDNOTES:**

1. Although General Electric (GE Nuclear) is now building two 1,350 MW Advanced Boiling Water Reactors in Taiwan (see Liaw and Lee, 1998), it is reluctant to do business in China without a stronger nuclear liability and insurance program (see Winston and McManamy, 1997).
2. Some light water reactors are now using a mixture of uranium and plutonium, also known as mixed-oxide fuel or MOX. The use of MOX is scheduled to increase with the blending of plutonium from decommissioned US and Russian nuclear weapons.
3. In David and Rothwell (1996b) HHI is a weighted average of diversity of (1) reactor vendor, (2) turbine-generator manufacturer, and (3) architect-engineer. This leads to a lower HHI.
4. The assumption of a 7% real discount rate is from Sinton (1998, p. 73), which discusses the terms of financing for Ling'ao.
5. The capital recovery factor includes return to capital and an allowance for depreciation. It is equal to $r\,(1 + r)^t / [\,(1 + r)^t - 1\,]$, where $r$ is the rate of return and $t$ is the life of the nuclear power plant. In the model a continuous time version is used. It is equal to $[e^{rt}\,(e^r - 1)] / (e^{rt} - 1)$.
6. The capacity factor is equal to $Q/(W \cdot h)$, where $Q$ is annual output in megawatt-hours, $W$ is megawatts, and $h$ is the number of hours per year. See Rothwell (1998).
7. This analysis assumes that all operation costs are fixed during one year. This is true for most operation and maintenance costs at nuclear power plants. See Rothwell (1999). It is equivalent to assuming a 100% capacity factor with regard to variable cost. However, when calculating cost per megawatt-hour, this analysis assumes that all nuclear power units operate at the same capacity factor. Future research should investigate learning reflected in the capacity factor and differentiate between fixed and variable operating cost.
8. Here, I focus on operating costs. A more complete model would consider the mean and variance of capital (construction and post-construction additions) costs under diversity and standardization. While early standardization lowers capital cost, it might increase its variance

due to the lack of learning from a diversity of plant designs. Standardization includes the probability that a design flaw could affect many plants.

9. In David and Rothwell (1996a), this equation is equivalent to $E( cs^{max} \mid n) = \mu + B\,\sigma\,( \log n )^{\beta}$. Here, I assume that both $B$ and $\beta$ are equal to 1.

10. The uniform series, present value factor is equal to $[ ( 1 + r )^{t} - 1 ] / r ( 1 + r )^{t}$, the inverse of the capital recovery factor. The continuous time version is used in the model.

11. In David and Rothwell (1996a), this equation is equivalent to $E(cs_3^{max} \mid M ) = \mu + A\,\theta\,M^{\alpha}$. Here, I assume that $A = 1$ and $\theta = \sigma$.

12. This is similar to the development of the Korean Standard Nuclear Plant. See Park (1998).

## TABLES

### Table 1: Chinese Nuclear Power Plants

| Plant | Province<br>$/kW | Type<br>Net MW | Date | Utility | NSSS | Turbine/<br>Generator | Architect/<br>Engineer | Constructo |
|---|---|---|---|---|---|---|---|---|
| Qinshan 1 | Zhejiang<br>~$2,500 | PWR<br>279 | 1994 | Qinshan NPC | CNNC, Japan<br>(Mitsubishi) | CNNC | CNNC | CNNC |
| Daya Bay 1<br>Daya Bay 2 | Guangdong<br>~$2,300 | PWR<br>2 x 944 | 1994 | Guangdong<br>NPJV | France<br>(Framatome) | France+UK<br>(GEC-Alsthom) | France+UK | France,<br>China |
| **Total in Operation** | | **2167 Net MW** | | | | | | |
| Qinshin 2-1<br>Qinshin 2-2 | Zhejiang<br>~$1,700 | PWR<br>2 x 610 | 2002<br>2003 | Qinshan NPC | CNNC, Korea,<br>France | US<br>(Westinghouse) | China, France | China |
| Ling'ao 1<br>Ling'ao 2 | Guangdong<br>~$1,700 | PWR<br>2 x 935 | 2003<br>2003 | Guangdong<br>NPJV | France<br>(Framatome) | France+UK<br>(GEC-Alsthom) | France+UK | China,<br>France,<br>Japan |
| Qinshan 3-1<br>Qinshan 3-2 | Zhejiang<br>~$2,500 | PHWR<br>2 x 665 | 2004<br>2006 | Qinshan NPC | Canada<br>(AECL) | Japan<br>(Hitachi) | US (Bechtel) | Canada,<br>China,<br>Korea |
| Lianyungang 1<br>Lianyungang 2 | Jiangsu<br>~$1,700 | WWER<br>2 x 950 | 2004<br>2005 | Lianyungang<br>NPJV | Russia | Russia | Russia | Russia |
| **Total under Construction** | | **6320 Net MW** | | | | | | |

Notes: Cost per kW is approximate.
AECL = Atomic Energy of Canada Ltd.
CNNC = China National Nuclear Corporation
GEC = General Electric Co. of the UK
GEC-Alsthom = Joint venture of GEC and Alcatel-Alsthom (France)
NPC = Nuclear Power Corporation
NPJV = Nuclear Power Joint Venture
PHWR = Pressurized Heavy Water Reactor
PWR = Pressurized Water Reactor
WWER = Water (Cooled)-Water (Moderated) Electricity Reactor

Source: Sinton (1998) and IAEA (2000).

**Table 2a: Parameter Values**

| Parameter | Definition | Units | Value |
|---|---|---|---|
| N | Number of units per stage | | 8 |
| k | Construction cost per kW | $/kW | $2,400 |
| gamma | Learning in construction | % | 10% |
| W | Capacity of units in MW | MW | 900 |
| c | Operating cost | $/MWh | $40 |
| sigma | Standard deviation in CS | $/MWh | $4 |
| x | Stages in Generation II | | 4 |
| r | Discount rate | % | 7% |
| CRF | Capital Recovery Factor | % | 8% |
| tau | Construction time | years | 5 |
| t2=t3 | Nuclear Power Plant Lifetime | years | 30 |
| t4 | Years to Generation II | years | 10 |
| d1 | Discount factor t=5 | % | 70% |
| d2=d3 | Present value of annuity | | 12.10 |
| d4 | Discount factor t=10 | % | 50% |
| alpha | Learning in Gen II operation | % | 50% |
| alpha* | where diversity = standard | % | 82% |

**Table 2b: Variables**

| Variable | Definition | Units | Eq | | | | |
|---|---|---|---|---|---|---|---|
| **M** | **Number of technologies** | | | **1** | **2** | **4** | **8** |
| n | Number of units in a set | | | 8 | 4 | 2 | 1 |
| d | Diversity | | | 0.125 | 0.250 | 0.500 | 1.000 |
| k(n) | Construction cost per MW | $/kW | 1 | $1,949 | $2,089 | $2,239 | $2,400 |
| K | Total capital cost | $B | 2b | $14 | $15 | $16 | $17 |
| K/MWh | Capital Cost/MWh | $/MWh | | $22.98 | $24.63 | $26.40 | $28.30 |
| C2 | Realized operating cost | $/MWh | 4 | $31.68 | $34.45 | $37.23 | $40.00 |
| $/MWh | Average Generation I cost | $/MWh | | $54.67 | $59.09 | $63.63 | $68.30 |
| TC2 | Total operating cost in Stage 2 | $B | | $2.0 | $2.2 | $2.3 | $2.5 |
| PV2 | Present value of TC2 | $B | 5 | $38 | $41 | $45 | $48 |
| k3 | Average K cost in Gen II | $/kW | 6 | $1,464 | $1,570 | $1,682 | $1,803 |
| k3/MWh | Capital Cost/MWh | $/MWh | | $17.27 | $18.51 | $19.83 | $21.26 |
| C3 | Realized C in Gen II | $/MWh | 8 | $27.68 | $28.80 | $29.23 | $28.69 |
| $/MWh | Average Generation II cost | $/MWh | | $44.95 | $47.30 | $49.06 | $49.94 |
| K3 | Discounted total K in Gen II | $B | | $30 | $32 | $34 | $37 |
| TC3 | Annual C per stage in Gen II | $B | | $1.7 | $1.8 | $1.8 | $1.8 |
| PVC3 | Present value of TC3 | $B | | $60 | $62 | $63 | $62 |
| PV3 | Expected costs in Gen II | $B | 9 | $89 | $94 | $97 | $98 |
| **C*** | **Present value of total costs** | **$B** | **10a** | **$71** | **$76** | **$80** | **$83** |

**FIGURES**

**Figure 1: World Nuclear Power Reactor Capacity**

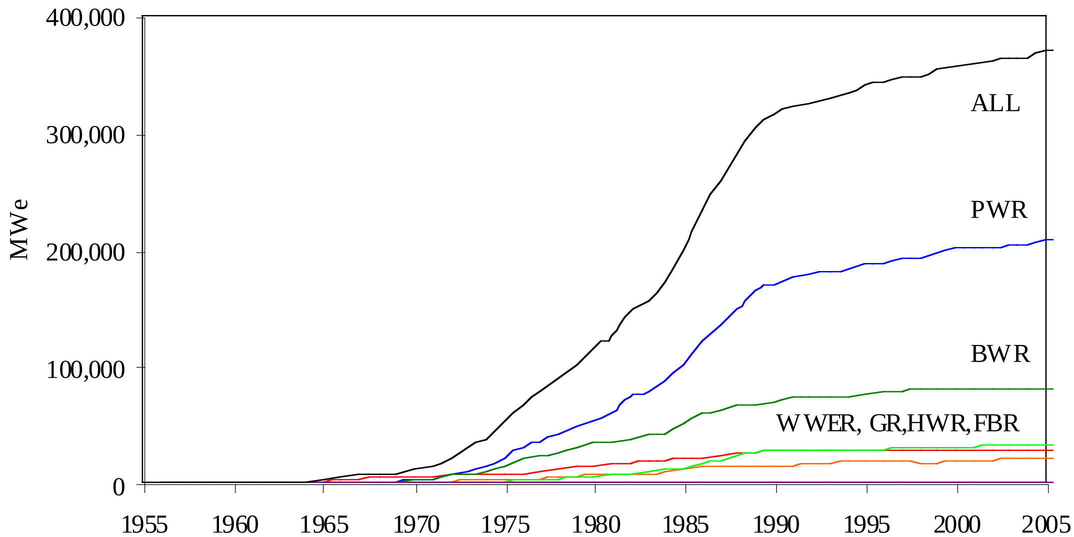


**Figure 2: Herfindahl-Hirschman Index for Nuclear Power Reactors in the World**

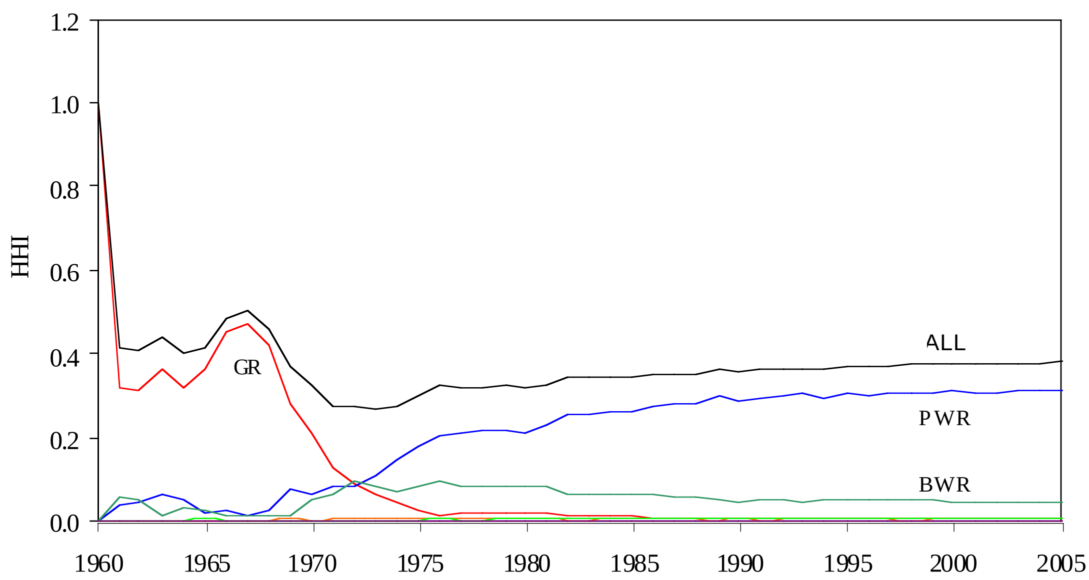

**Figure 3: HHI for Nuclear Power Reactors in Vendor Countries**

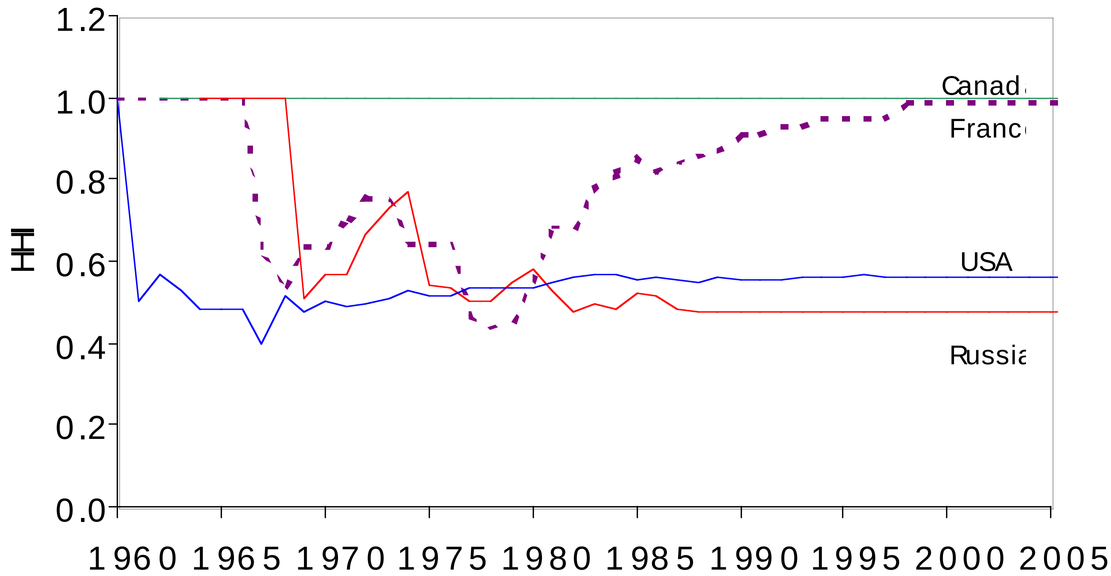


**Figure 4: HHI for Nuclear Power Reactors in East Asia**

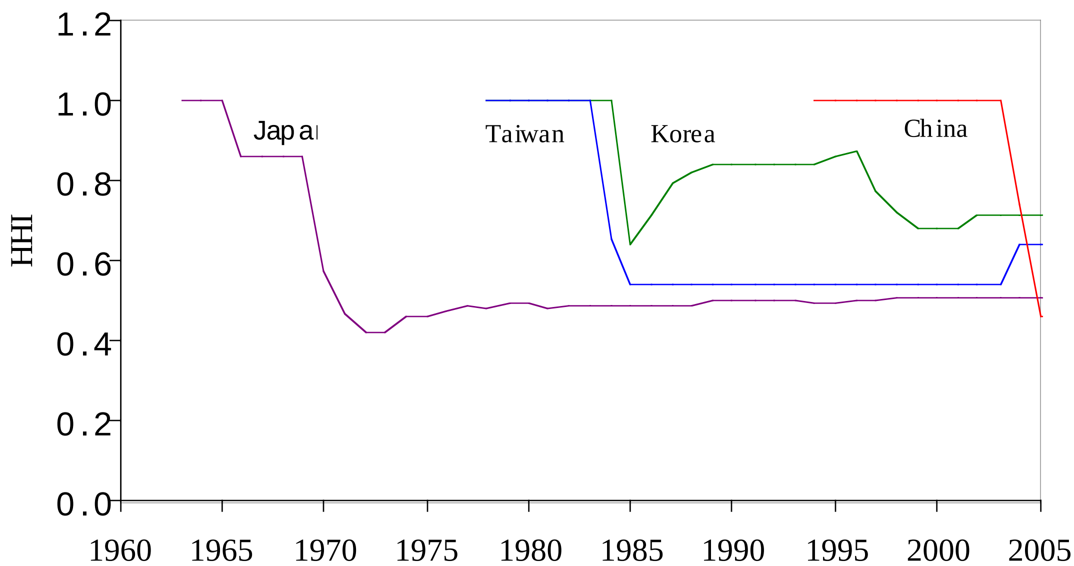


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**Figure 5: Economies of Scale in Nuclear Power Unit Construction**

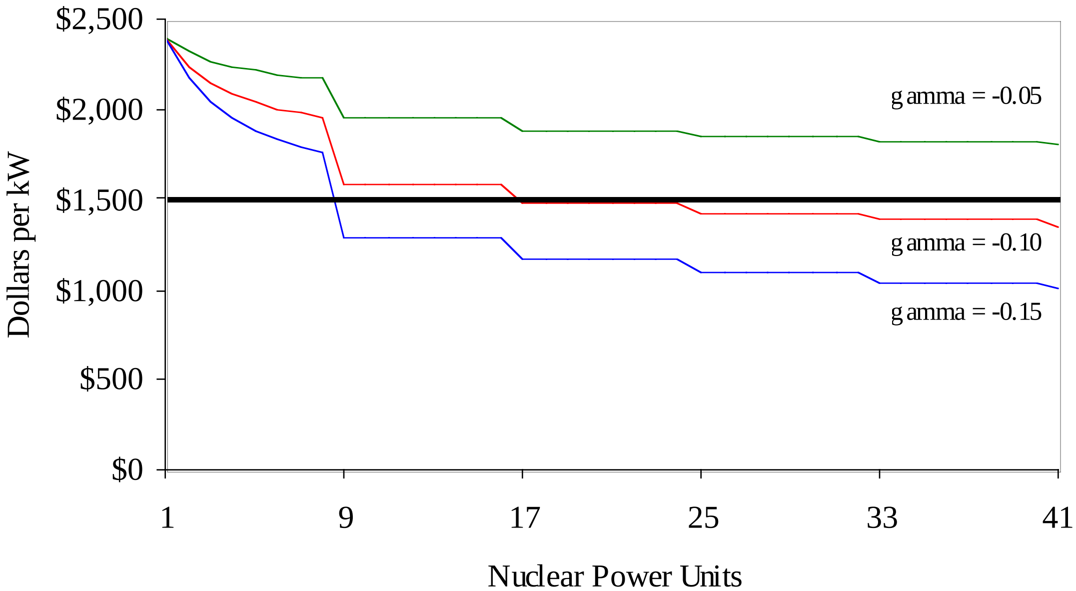



**Figure 6: The Influence of the Learning Parameter in Operations on Present Value**

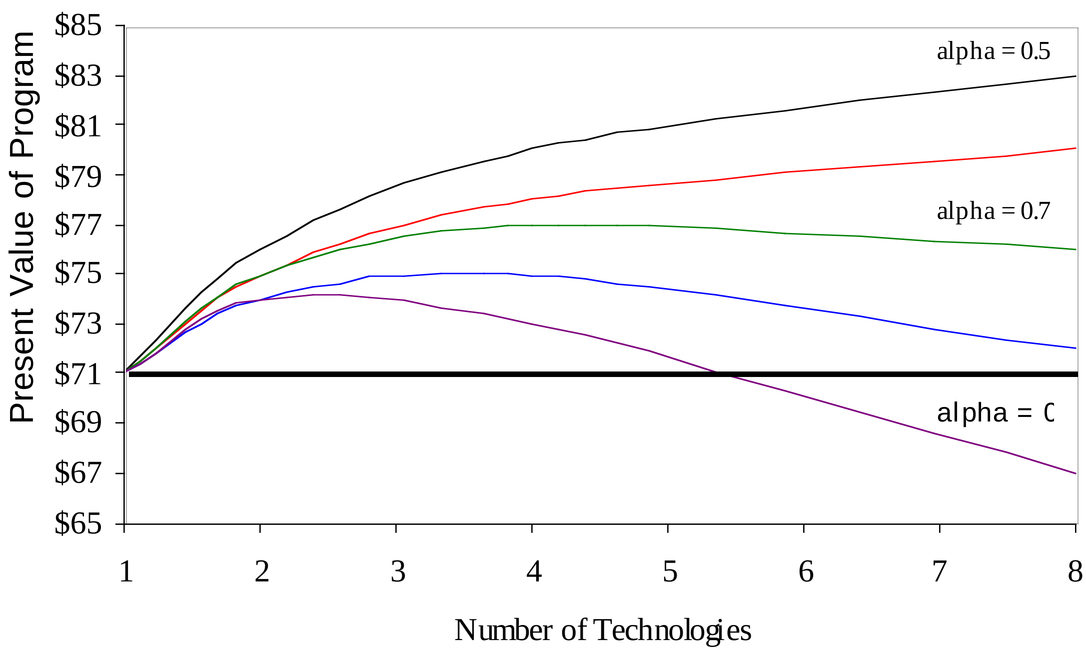
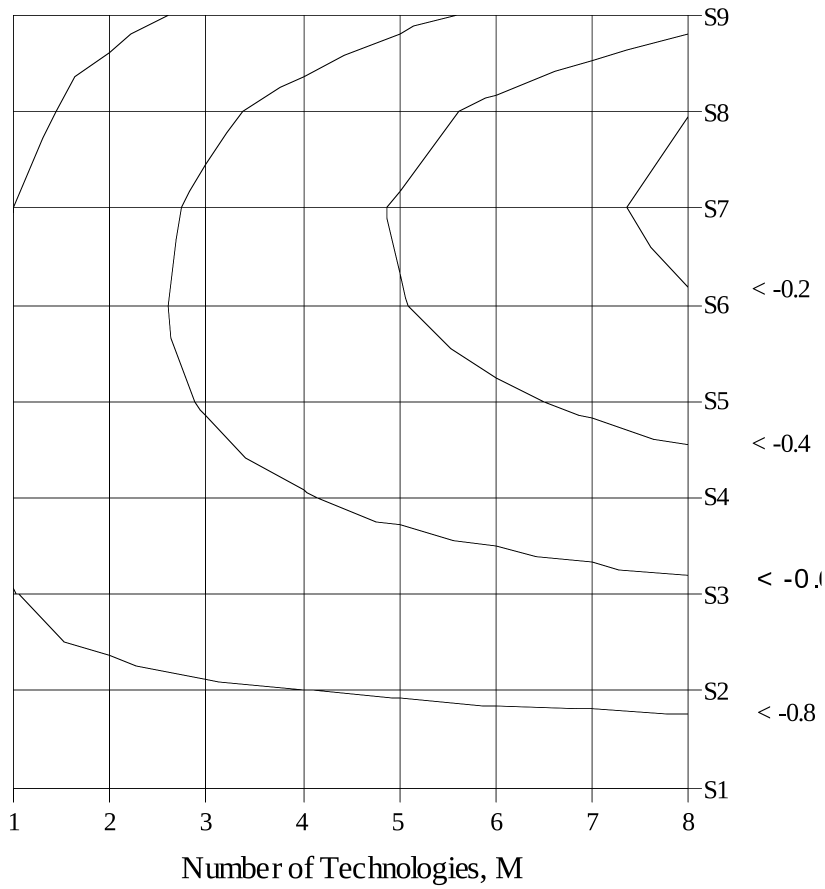


**Figure 7: Case 2 Second Order Conditions**




Note: S1 ⇒ α = 0.1, S2 ⇒ α = 0.2, …, S9 ⇒ α = 0.9, where γ = 1

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